National Aeronautics and Space Administration

Materials Characterization

Phase Contrast X-Ray Imaging

NASA Marshall Space Flight Center

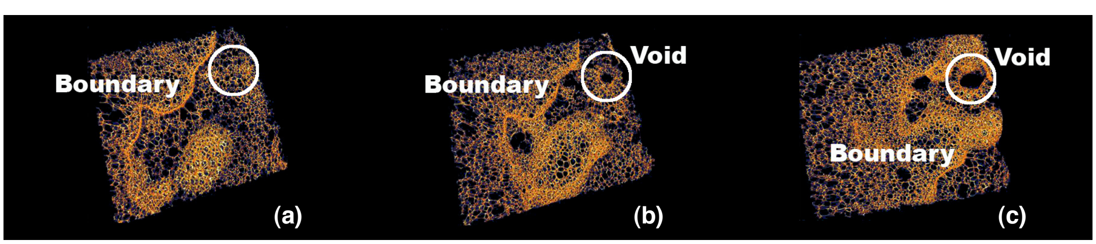
Lightweight, high-performance materials, such as insulating foam and leading edge composites used for space vehicles, require nondestructive evaluation (NDE) techniques for quality inspection and control. Foam debris generation led to the loss of the Space Shuttle *Columbia* and its crew in 2003 and highlighted the critical need to better inspect and control foam quality. However, low-density foam, such as that used to insulate the Space Shuttle External Tank, is hard to adequately inspect using traditional NDE tools. The foam's cellular structure does not absorb X-rays well, resulting in low contrast images that do not accurately reveal flaws. This investigation tested the feasibility of using coherence of X-rays for phase imaging (instead of absorption-based imaging) to better identify foam flaws. Adding the phase information of X-rays into image formation significantly enhanced image contrast and sensitivity, revealing material flaws that were not apparent in images produced by absorption-based X-ray radiography and computed tomography. Detailed information on the intrinsic quality of the foam, including its defects and behavior when stressed with loads, was provided to the Engineering Directorate at NASA's Marshall Space Flight Center where the data are being used to improve foam quality and processing for future Space Shuttle missions as well as for materials and materials processing that support the Vision for Space Exploration.

Task Description

The Advanced Materials for Exploration (AME) study tested a new NDE technique. The following tasks were completed:

1. Developed and tested phase contrast two-dimensional (2D) and three-dimensional (3D) imaging capability for NDE of foams
2. Used NDE to analyze the variations of defects in foam insulation samples with different depths from the outer layers to inner layers
3. Evaluated the suitability of the imaging technique for broad application with other advanced materials
4. Developed capability to load samples and make *in-situ* imaging observations showing how the loads affected the sample.

This 18-month effort was initiated in FY04 and completed in April 2006.



Phase contrast 3D images (a), (b), and (c) show a zigzag boundary and defects inside the foam corresponding to internal foam regions at different depths with (c) being the deepest. The circled void has a dimension of more than 1.5 mm (0.6 in.) along the foam rise direction.

advanced materials for exploration

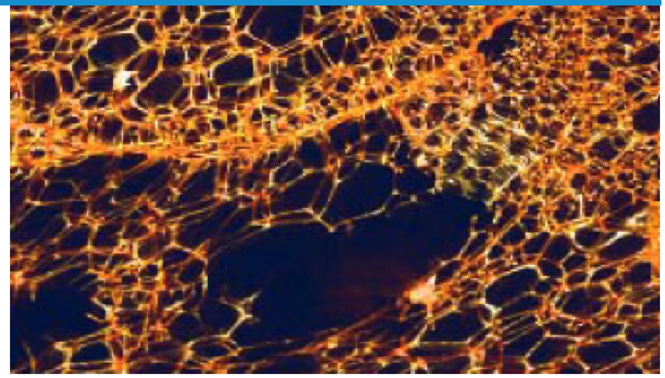
PHASE CONTRAST X-RAY IMAGING

Results

This study tested Shuttle foam insulation BX-250, a polyurethane foam applied by hand to the domes, ramps, and a few other areas of the External Tank. The Principal Investigator successfully competed for synchrotron beamtime at the Department of Energy's Advanced Photon Source in Chicago, IL, one of the few places in the world capable of producing high-energy X-rays required for phase contrast imaging. To create each tomographic (3D) image, samples were bombarded with X-rays, and about 800 projection images were taken over a 180-degree angular range and recorded by a high-resolution CCD camera.

The resultant images from this study provided reliable and detailed data about the foam structure and its flaw formation that was previously impossible to obtain. Images revealed a great variation and high anisotropy in foam structure in terms of cell size, shape, and wall and strut thickness. By analyzing a series of photos taken at different depths inside the foam sample, investigators found the foam is made up layers of cells that are separated by complicated zigzag boundaries characterized by highly irregular cells with wall thicknesses several times that of the regular cells in the layers. These marked differences in the layers and boundaries impact the foam's properties and behavior, in particular how the foam stands up to loading, such as that experienced during a Shuttle launch. The images reveal voids (major defects) throughout the foam. The voids vary considerably in size, but they tend to form more readily along the boundaries and the interfaces between the foam and aluminum substrates.

Investigators conducted pressure tests that showed the foam's strength varied considerably from one region to another as a result of variations in the foam's quality and density. To further test the foam's response to stress, the investigator developed and tested an *in-situ* loading method. Preliminary loading experiments confirmed that the phase contrast images accurately revealed the defects inside the foam and showed how these flaws could result in foam failure. For example, when pressure was exerted, the foam cracked at the boundary knit-lines.



Phase contrast 3D imaging reveals how pressure loading induced internal foam cracking and/or spalling at a knit line.

Experiments also examined lightweight composites, including carbonized foam and composites of polyethylene-epoxy and carbon-carbon. Phase contrast images revealed structural non-uniformity that would affect on the materials' physical properties, reliability and performance.

Potential Future Activities

This feasibility study demonstrated the great potential of phase contrast X-ray imaging to non-destructively characterize advanced lightweight materials and/or structures. Combined *in-situ* loading and image visualization methods offer a powerful way to better understand how foam behaves when stressed. The next step is to develop an in-house phase contrast X-ray imaging tool that would enable low-density material structures to be non-invasively visualized with sufficient sensitivity and resolution to identify flaws.

Capability Readiness Level (CRL)

This AME task tested a new technique for non-destructive evaluation of foam (CRL-3). This insight into the foam structure and response to loading will help result in better foam insulation and safer space exploration vehicles.

Principal Investigator

Dr. Zhengwei Hu, BAE Systems, Zhengwei.Hu-1@nasa.gov, (256) 544-3805

AME Contact/Project Lead

Beth Cook, NASA/MSFC, Beth.Cook@nasa.gov, (256) 544-2545

National Aeronautics and Space Administration

Marshall Space Flight Center
Huntsville, AL 35812

www.nasa.gov

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